Hydrological Environment of Bangladesh

Bangladesh's hydrological environment is complex and dynamic, shaped by its extensive river systems, low-lying topography, and proximity to the Bay of Bengal. The country experiences a monsoon-dominated climate, with heavy rainfall during the summer months, leading to significant variations in water levels throughout the year.

Rainfall:

Bangladesh receives an average annual rainfall of 2,300 mm, with variations ranging from 1,200 mm in the western regions to 4,400 mm in the northeastern hills. The monsoon season, from June to October, accounts for over 80% of the annual rainfall.

Water Sources:

Bangladesh's primary water sources are its vast network of rivers, groundwater reservoirs, and rainwater harvesting systems. The country is home to over 250 rivers, which drain into the Bay of Bengal. The Ganges, Brahmaputra, and Meghna rivers are the largest and most important, providing water for agriculture, transportation, and domestic use. Groundwater is another significant source of water, particularly in the western and central regions. Rainwater harvesting is widely practiced, especially in rural areas, to supplement water supplies during dry periods.

Rivers:

The river systems of Bangladesh play a crucial role in the country's hydrological cycle. The rivers act as a natural drainage system, carrying excess water from the monsoon rains to the sea. They also replenish groundwater reserves and provide fertile land for agriculture. However, the rivers are also a source of flooding, particularly during the monsoon season, when heavy rainfall can overwhelm the drainage capacity of the river systems.

Water Discharge:

The discharge of rivers in Bangladesh varies significantly throughout the year. During the monsoon season, river discharge rates can reach up to 1 million cubic meters per second. However, during the dry season, discharge rates can drop to as low as 10,000 cubic meters per second. These variations in river discharge pose challenges for water management and infrastructure development.

Other Hydrological Factors:

In addition to rainfall, water sources, rivers, and water discharge, other factors influence Bangladesh's hydrological environment. These factors include:

- Tidal influences: The Bay of Bengal exerts a strong tidal influence on Bangladesh's coastal regions, affecting water levels and salinity.
- Land-use patterns: Deforestation and urbanization can alter water infiltration rates and increase runoff, contributing to flooding and water scarcity.
- Climate change: Rising sea levels and changes in rainfall patterns are expected to have significant impacts on Bangladesh's hydrological environment, increasing the frequency and intensity of floods and droughts.

Managing Bangladesh's hydrological resources effectively is essential for the country's sustainable development. This requires a comprehensive approach that addresses issues such as flood control, water resource management, drought mitigation, and adaptation to climate change.

Wetland Status of Bangladesh

Wetlands are the most useful natural productive ecosystem in the world. Estimates indicate that about 6.4 per cent of lands of the world are wetlands. Wetlands are a vital link between land and water in Bangladesh. More than two third of Bangladesh may be classified as wetland according to the definition enunciated in the Ramsar Convention. About 6.7 per cent of Bangladesh is always under water, 21 per cent is deeply flooded (more than 90 cm) and 35 per cent experience shallow inundation (FAO, 1988).

The total area of Wetlands in Bangladesh is about seven or eight million hectares, which constitutes about 50 per cent of the land surface of the country. Bangladesh floodplains are one of the world’s most important wetlands, harbouring hundreds of species of fish, plants and wildlife. The wetlands in Bangladesh encompass a wide variety of dynamic ecosystems ranging from mangrove forest (about 577, 100 ha), natural lakes, man-made reservoir (Kaptai lake), freshwater marshes (about 400 haors), oxbow lakes (about

54488 ha, locally known as baors), freshwater depressions (about 1,000 beels), fish ponds and tanks (about 147, 000 ha), estuaries and seasonal inundated extensive floodplains.

Several wetlands in Bangladesh are of national and international significance. Eight wetlands, where ecosystems have reached or threatened to reach a critical state, have been declared as ecologically critical areas (ECA) by the Ecologically Critical Area Ordinance, 2010, under the Bangladesh Environment Conservation Act, 1995. These wetlands are (1) Hakaluki Haor (Moulvibazar and Sylhet district); (2) Tanguar Haor (Sunamganj district); (3) Marjat Baor (Jhenidah district); (4) Gulshan-Baridhara Lake (Dhaka city); (5) the river systems in Dhaka and Narayanganj district - the Buriganga River, the Shitalakhya River, the Turag River, and the Balu River; (6) the Sundarban mangrove (Khulna, Satkhira, and Bagerhat district); (7) Sonadia Island (Cox's Bazar district); and (8) St. Martin's Coral Island (Cox's Bazar district).

Bangladesh is highly rich in wetlands. Aerial photographs show rivers and streams, freshwater lakes and marshes, haors, baors, beels, jheels, ponds, water storage reservoirs, floodplains, flooded cultivated paddy fields and estuarine and mangrove systems. Millions of man-made ponds, khals and tanks also turn into natural wetlands and serve us without any rest. They are considered as ''biological supermarket''.

Bangladesh floodplains are one of the world's most important wetlands and home to hundreds of species of fish, plants, birds and other wildlife. These wetlands support over 260 fish species, 257 species of birds, 40 species reptiles, 29 species of mammal, 9 species amphibians and hundreds of thousands of migrating birds. Among the estimated 5,000 species and some flowering plants and 1,500 vertebrates in the country, up to 300 plant species and some 400 vertebrate species are judged to be dependent on wetlands for all or part of their life span.

These wetlands provide a critical source of income and nutrition for millions of rural Bangladesh's poorest people's intensive use for agriculture, fishing and collection of other aquatic resources helps to support a population of over 800 people per square kilometre. Inland fisheries are particularly important: the four million hectares regularly inundated wetlands contribute about 46 per cent of all fish consumed by the rural people. Over 70 per cent of households in the floodplains catch fish either for income or food and about 60 per cent of animal protein consumption comes from fish. In fact the Bengali way of life is defined by use of modified wetlands in the traditional saying 'Mache Bhate Bangali' literally meaning rice and fish eating Bengali.

For Environmental Importance; Wetlands also help to reduce the impacts from storm damage and flooding, maintain good water quality in rivers, recharge groundwater, store carbon, help to stabilise climatic conditions and control pests, prevent flooding by holding water much like sponge, fisheries production, recreation, natural heritage value, biomass production, keep rivers level normal and filter and purify the surface water. Mineral resources found in the Haor region are coal, crude oil, glass sand, gravel, limestone, natural gas, peat, white clay. About 90 per cent of the total gas production of the country is obtained from the Haor district.

Wetlands cover about 9 per cent of the earth's surface and are estimated to contain around 35 per cent of global terrestrial carbon. Wetlands act as sinks for carbon dioxide and other greenhouse gases. For agriculture it supports fertile soils, reduces erosion, provides shade, wind buffering, assists in drought in the North-West region of Bangladesh.

Wetlands also provide tremendous economic benefits, including water supply (quantity and quality), fisheries, agriculture, through the maintenance of water tables and nutrient retention in floodplains; timber and other building materials; energy resources, such as peat and plant matter; wildlife resources; transport; a wide range of other wetland products, including herbal medicines; and recreation and tourism opportunities.

Over the last three decades, massive physical infrastructures in the form of rural roads and flood embankments have been developed in the wetlands including floodplains and haor areas. Many of these infrastructures have disregarded local topographic conditions and natural water flow directions which have often resulted in loss of connectivity, reduced drainage, increased reclamation of wetlands and waterlogging; all have affected the local surface water regime. The critical point of such development activities in the wetlands led the transformation very rapidly at a massive scale.

'In the Ganges-Brahmaputra floodplain area, about 2.1 million hectares of wetland have been lost to Flood Control, Drainage and Irrigation development projects (FCDI). Human interference in the wetlands has been damaging the fragile ecosystem and to long-term sustainability of the wetlands. Over the past 250 years or so, 53 per cent of wetland in the US have been lost due to human activities. Wetlands are declining and more than 64 per cent of the world's wetlands have been lost.'

As a whole, degradation of wetlands has caused several problems;

All the rivers flowing through Bangladesh originate outside the country and these carry heavy loads of silt, sediments and debris, including domestic, agrochemical and industrial wastes, from far-way places.

Extinction and reduction of wildlife, extinction of many indigenous wild and domesticated rice varieties, loss of many indigenous aquatic plants, herbs, shrubs and weeds, loss of natural soil nutrients, loss of natural water reservoirs and of their resultant benefits,

Increase in the occurrence of flooding and degeneration of wetland based ecosystems, occupations, socio-economic institutions and cultures. The wetlands of the whole country are the dumping grounds for these sediments and pollutants and flushing out of material to the sea is quite slow.

The main water related problems are flash flood, drainage congestion due to sedimentation and loss of connectivity between haor and rivers, river bank and wave erosion and poor navigability.

Whatever industries we already have are enough to render the entire wetlands of Bangladesh including the river system 'biologically dead' if the conditions now prevailing are allowed to continue further.

There are some initiatives taken by the Government of Bangladesh for wetland conservation;

(a) Set up Ministry of Environment and Forest (1998)

(b) Formation of National Conservation Strategy

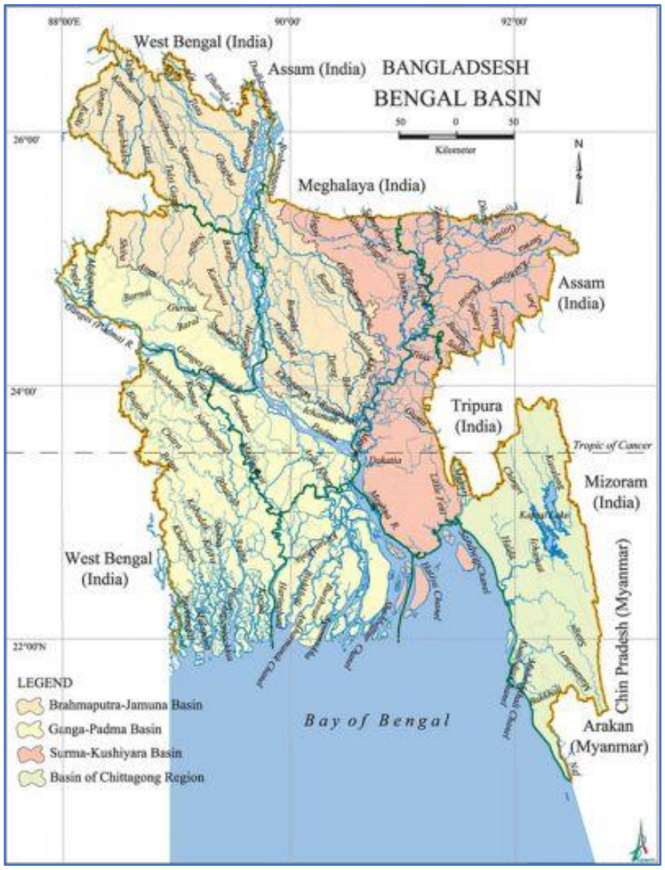
(c) National Environment Policy (1992)

(d) Became signatory of Ramsar Convention (1992)

(e) Sustainable environment management program (1996)

we should work on some awareness campaign;

- Meeting with stakeholders group,
- Discussion session
- Debate on specific issues,
- Observation of national and world day's
- Staging folk dramas and holding workshop as well as seminars
- School awareness programs and demonstration of sustainable farming systems (includes fishing and bird hunting)

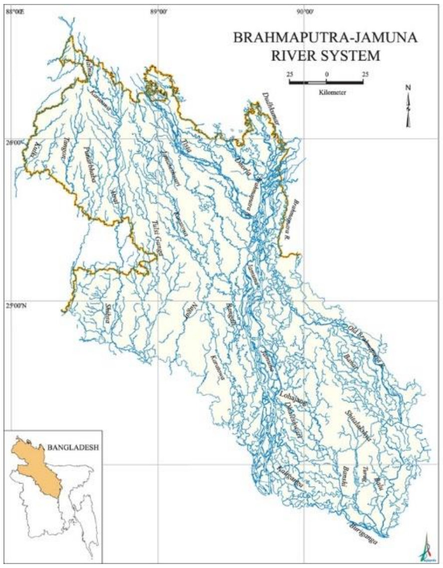


River System of Bangladesh

River and Drainage System the rivers of Bangladesh are very extensive and distinguish both the physiography of the country and the life of the people. Bangladesh is called a land of rivers as it has about 700 rivers including tributaries. The rivers are not, however, evenly distributed. For instance, they increase in numbers and size from the northwest of the northern region to the southeast of the southern region. The total length of all rivers, streams, creeks and channels is about 24,140 km. In terms of catchment's size, river length and volume of discharge, some of these rivers are amongst the largest on the earth. Usually the rivers flow south and serve as the main source of water for irrigation and as the principal arteries of commercial transportation. The rivers also provide sweet water fish, an important source of protein. A large segment of population is thus engaged in the fishing sector. On the other hand, widespread riverbank erosion and regular flooding of the major rivers cause enormous hardship and destruction of resources hindering development. But it is also true to say that the river system brings a huge volume of new silt to replenish the natural fertility of the agricultural land. Moreover, the enormous volume of sediments that the rivers carry to the bay of bengal each year (approximately 2.4 billion tons) builds new land along the sea front, keeping hope alive for future extension of settlement. Finally, during the monsoon, rivers also drain excess discharge to the Bay. Thus this great river system is the country's principal resource as well as its greatest hazard. The system can be divided into four major networks: (1) brahmaputra-jamuna river system, (2) ganges-padma river system, (3) surma-meghna river system, and (4) chittagong region river system.

The first three river systems together cover a drainage basin of about 1.72 million sq km, although only 7% of this vast basin lies within Bangladesh. The combined annual discharge passing through the system into the Bay of Bengal reaches up to 1,174 billion cu

m. Most of the rivers are characterised by fine sandy bottoms, flat slopes, substantial meandering, banks susceptible to erosion, and channel shifting.

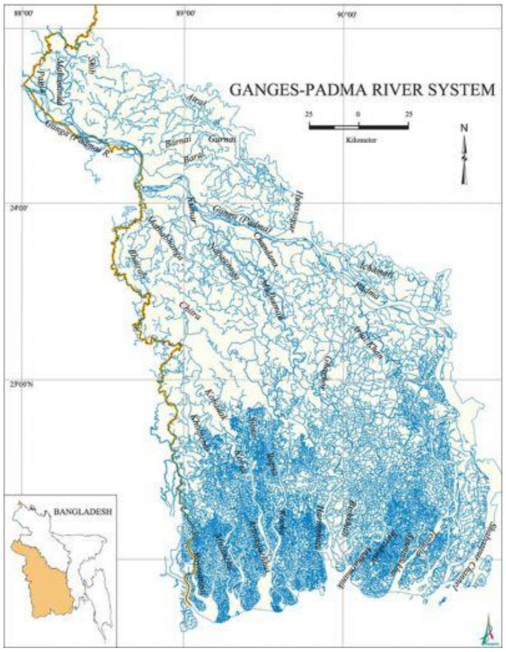


Brahmaputra-Jamuna system the Brahmaputra-Jamuna river is about 280 km long and extends from northern Bangladesh to its confluence with the ganges. Before entering Bangladesh, the brahmaputra has a length of 2,850 km and a catchment area of about 583,000 sq km. The river originates in Tibet as the Yarlung Zangbo Jiang and passes through Arunachal Pradesh of India as Brahmaputra (son of Brahma). Along this route, the river receives water from five major tributaries, of which Dihang and Luhit are prominent. At the point where Brahmaputra meets the tista in Bangladesh, it is called the jamuna. The Brahmaputra-Jamuna throughout its broad valley section in Assam and in Bangladesh is famous for its braided nature, shifting sub channels, and for the formation of chars (island/sandbars) within the channel.

The recorded highest peak flow of Brahmaputra-Jamuna is 98,000 cusec in 1988; the maximum velocity ranges from 3-4 m/sec with a depth of 21-22m. The average discharge of the river is about 20,000 cusec with average annual silt load of 1,370-tons/sq km. The average slope of the Jamuna is about 1:11,400; however, the local gradient differs quite considerably from the average picture.

Within Bangladesh, the Brahmaputra-Jamuna receives four major right-bank tributaries - the dudhkumar, dharla, Tista and hurasagar. The first three are flashy, rising in steep catchment on the southern side of the Himalayan system between Darjeeling and Bhutan. The Tista is one of the most important rivers of the northern region. Before 1787 it was the principal water source for the karatoya, atrai and Jamuneshwari. A devastating flood of 1787 brought in a vast amount of sand wave through the Tista and choked the mouth of the Atrai; as a result the Tista burst into the course of the ghaghat river. The Tista has kept this course ever since. The present channel within Bangladesh is about 280 km long, and varies between 280 to 550 m in width. It joins the Brahmaputra just south of Chilmari upazila. The Dharla and Dudhkumar flow parallel to Tista. The Dharla is a fast flowing river in the monsoon but with the fall of water level it becomes braided. The Dudhkumar is a small river and flows southeast to join the Brahmaputra. The combined discharge of the Atrai and Karatoya passes through the Hurasagar to the Jamuna.

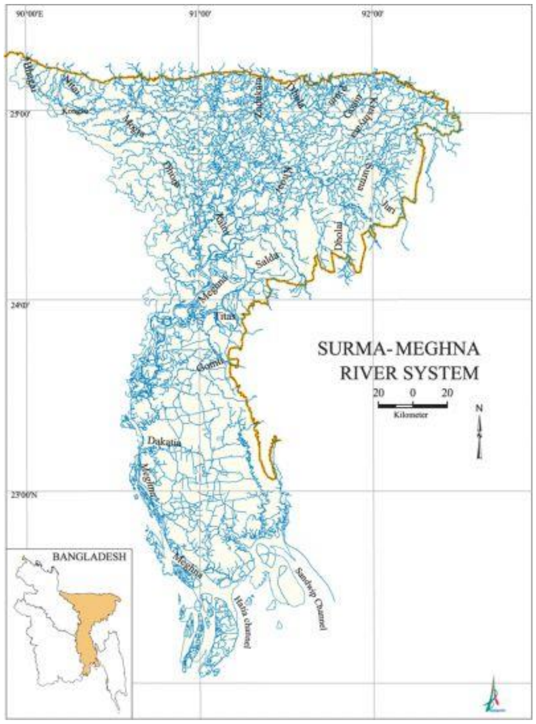
The old brahmaputra and the dhaleshwari are the important left bank distributaries of the Jamuna. Prior to the 1787 Assam flood, the Brahmaputra was the main channel; since then the river has shifted its course southward along the Jhenai and Konai rivers to form the broad, braided Jamuna channel. The old course, named the Old Brahmaputra is now essentially a high-flow spill channel, active only during the monsoon. Taking off at Bahadurabad, the Old Brahmaputra flows southeast, passes by Jamalpur and Mymensingh towns and joins the Meghna at Bhairab Bazar. Its average gradient is 4.76 cm/km. Along its southeasterly journey, Dhaleshwari bifurcates at least twice. Two of its important branches are the Kaliganga and buriganga. The Dhaleshwari eventually meets the Shitalakshya at Narayanganj.



The Ganges-Padma system is part of the greater Ganges system. The Ganges has a total length of about 2,600 km and a catchment area of approximately 907,000 sq km. Within Bangladesh, Ganges is divided into two sections - first, the Ganges, 258 km long, starting from the western border with India to its confluence with Jamuna at Goalandaghat, some 72 km west of Dhaka. The second is the Padma, 126 km long, running from Goalandaghat confluence to Chandpur where it joins the Meghna. The Padma-Ganges is the central part of the deltaic river system with hundreds of rivers. The total drainage area of Ganges is about 990,400 sq km of which only 38,880 sq km lie in Bangladesh.

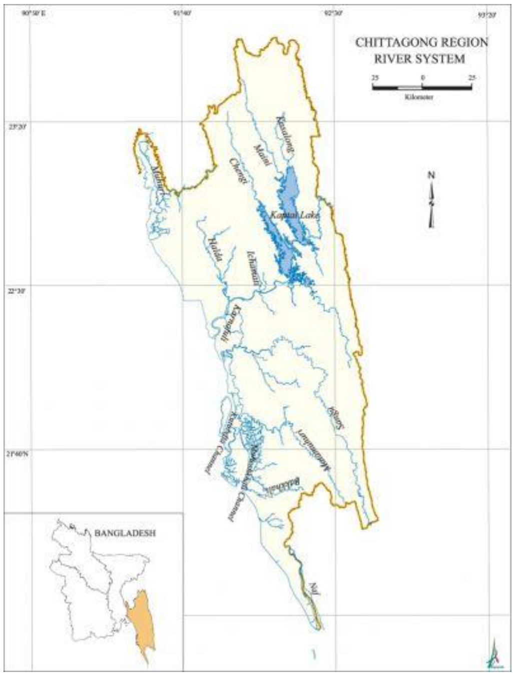
The recorded highest flow of Ganges was 76,000 cumec in 1981, and the maximum velocity ranging from 4-5 m/sec with depth varying from 20m to 21m. The average discharge of the river is about 35,000 cumec with an approximate annual silt load of 492 tons/sq km. The average gradient for the reach between Allahabad to Benaras is 1:10,500, from Farakka (India) to Rampur-Boalia in Rajshahi (Bangladesh) is 1:18,700, from Rampur-Boalia through Hardinge Bridge to Goalandaghat is 1:28,000. The slope flattens to 1:37,700 for a distance of 125 km from Goalandaghat to Chandpur. Within Bangladesh, the mahananda tributary meets the Ganges at

Godagari in Rajshahi and the distributary Baral takes off at Charghat on the left-bank. The important distributaries taking off on the right-bank are the Mathabhanga, gorai-madhumati, Kumar, and arial khan.



The Surma-Meghna system the Meghna is the longest (669 km) river in Bangladesh. It drains one of the heaviest rainfall areas (eg, about 1,000 cm at Cherapunji in Meghalaya) of the world. The river originates in the hills of Shillong and Meghalaya of India. The main source is the barak river, which has a considerable catchment area in the ridge and valley terrain of the Naga-Manipur hills bordering Myanmar. The Barak-Meghna has a length of 950 km of which 340 km lie within Bangladesh. On reaching the border with Bangladesh at Amalshid in Sylhet district, the Barak bifurcates to form the steep and highly flashy rivers surma and kushiyara. The Surma, flowing on the north of the Sylhet basin, receives tributaries from the Khasia and Jaintia hills of Shillong. Some of the important tributaries of these two rivers are Luba, Kulia, shari-goyain, Chalti-nadi, Chengar-khal, piyain, Bogapani, Jadhukata, Someshwari and kangsa. The Surma meets the Meghna at Kuliarchar upazila of Kishoreganj district. The Kushiyara receives left bank tributaries from the tripura hills, the principal one being the manu. Unlike the Surma, the tributaries of the Kushiyara are less violent, although prone to producing flash floods, due in part to the lesser elevations and rainfall of Tripura hills.

Between the Surma and Kushiyara, there lies a complex basin area comprised of depressions or haors, meandering flood channels, and abandoned river courses. This area remains deeply flooded in the wet season. The two rivers rejoin at Markuli and flow via Bhairab as the Meghna to join Padma at Chandpur. The major tributaries of any size outside the Sylhet basin are the Gumti and khowai rivers, which rise in Tripura. Other hilly streams from Meghalaya and Assam join the Meghna. The total drainage area of the Meghna up to Bhairab Bazar is about 802,000 sq km, of which 36,200 sq km lie in Bangladesh. The peak flow of the Meghna is 19,800 cu m/sec, and the maximum velocity range from 1-2 m/sec with depth varying from 33m to 44m. The average discharge of the river is about 6,500 cu m/sec. It has a steep slope while flowing in the Indian hilly part. At flood stages, the slope of the Meghna downstream at Bhairab Bazar is only 1:88,000. In terms of drainage pattern, the Meghna exhibits a meandering channel, and at some places it reflects an anastomosing pattern.



The Chittagong Region system the rivers of Chittagong and chittagong hill tracts are not connected to the other river systems of the country. The main river of this region is karnafuli. It flows through the region of Chittagong and the Chittagong Hills. It cuts across the hills and runs rapidly downhill to the west and southwest and finally to the Bay of Bengal. chittagong port is located on the bank of Karnafuli. The river has been dammed upstream at Kaptai to create a water reservoir for hydroelectric power generation. Other important rivers of the region are the feni, Muhuri, sangu, matamuhuri, Bakkhali, and naaf.

The four mighty river systems flowing through Bangladesh drain an area of some 1.5 million sq km. During the wet season the rivers of Bangladesh flow to their maximum level, at about 140,000 cusec, and during the dry period, the flow diminishes to 7,000 cusec. All the estuaries on the Bay of Bengal are known for their many estuarine islands. [Mohd Shamsul Alam]

Bibliography MAH Khan, 'Environmental aspects of surface water development projects in Bangladesh'; in AA Rahman *et al* ed, *Environment and Development in Bangladesh,* Vol 2, University Press Ltd, Dhaka, 1990; Haroun Er Rashid, *Geography of Bangladesh*, University Press Ltd, Dhaka, 1991.

Costal Zones

Coastal zone of Bangladesh is geomorphologically and hydrologically dominated by the Ganges Brahmaputra Meghna (GBM) river system and Bay of Bengal. The coastal zone of Bangladesh covers an area of 47,201 km2, 32% of the country, being the landmass of 19 districts (Figure 1). Around 35 million people, representing 29% of the population, live in the coastal zone. Coastal zone of Bangladesh consists of 19 coastal districts that are Jessore, Narail, Gopalganj, Shariatpur, Chandpur, Satkhira, Khulna, Bagerhat, Pirozpur, Jhalakati, Barguna, Barisal, Patuakhali, Bhola, Lakshmipur, Noakhali, Feni, Chittagong, and Cox's Bazar [1]. Depending on geographic features, coastal zone of Bangladesh consists of three parts, (a) The eastern zone, (b) The central zone, (c) Western zone.

The western region known as Ganges tidal plain, comprises the semi-active delta and is crisscrossed by numerous channels and creeks. The central region is the most active and continuous processes of accretion and erosion. Meghna river estuary lies here in this zone. The eastern region is covered by hilly area that is more stable [2]. The coastline is 710 km long which is composed of the interface of various ecological and economic systems, including mangroves (world largest mangrove forest covers 6,017 km2), tidal flat. Estuaries, sea grass, about 70 islands, accreted land, beaches, a peninsula, rural settlements, urban and industrial areas, and orts [3,4]. Many of the coastal inhabitants are poor, and the population is exposed to both natural disasters and man-made hazards. Climate change driven events like sea level rise, cyclone, storm surge, coastal inundation, salinity intrusion and land erosion are main the natural disasters (Figure 1) [4,5].CZ of BD is suffering from a wide range of climate change driven hazards and anthropogenic problems. So this vast coastal area needs management and holistic framework for sustainable development, conservation of coastal ecosystems and safety of coastal communities. The coastal management and development programs of the country took place in the early 1960s through undertaking a number of initiatives such as construction of coastal embankments, building coastal reenbelt, and land reclamation, community based management and delta development [4].

COASTAL HABITAT AND BIODIVERSITY OF BANGLADESH

Coastal areas are mostly rich bio-diversified. Western part is covered by world largest angrove forest. The Sundarbans support a very rich and diverse fish fauna of 120 species and over 270 species of birds which provides ivelihoods to about 300,000 people at certain seasons of the year working in different trades. Some of coastal areas are carpeted by seagrass with different species. A total of 165 species of seaweed belonging to 77 genera have been reported (Figure 2) [3,6-8].

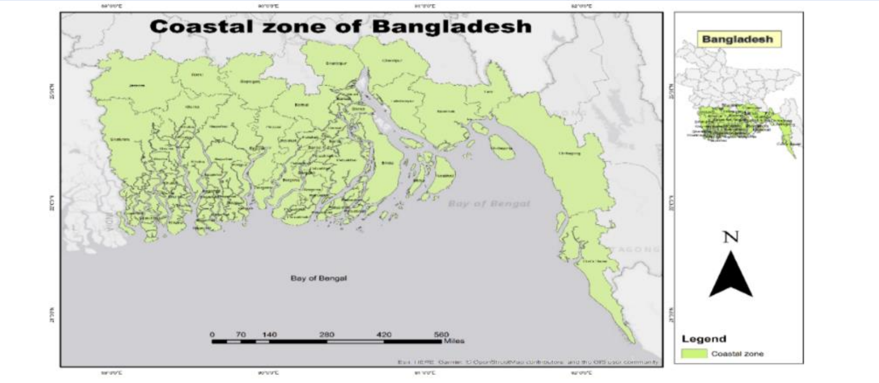


Figure 1: Coastal zone of Bangladesh.

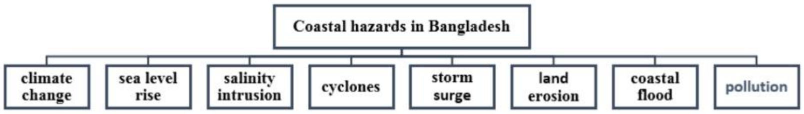


Figure 2: Coastal major hazards in Bangladesh coast.

COASTAL HAZARDS IN BANGLADESH COAST

Climate change brings a significant coastal hazards. Bangladesh is one of the country's most likely to suffer adverse impacts from anthropogenic climate change. Although angladesh emits less than 0.1% of global greenhouse gas emissions [9]. It is one of major coastal risks in Bangladesh because it is associated with other natural hazards in a complex way. A 1 m rise in sea level would submerge a full 18% of the total land area in Bangladesh [10]. A research showed that deeply flooded area (depth above 100 cm, duration more than 9 months) would increase by 29% (from the base year 2000) due to 88 cm SLR [11]. The total amount of salinity affected land in Bangladesh was 83.3 million hectares in 1973, which had been increased up to 102 million hectares in 2000 and the amount has raised to 105.6 million hectares in 2009 and continuing to increase [12]. With 50% of the land less than 8 m above sea level, and a coastline of some 600 km, coastal flooding is a common problem [13]. Bangladesh is especially vulnerable to tropical cyclones with around 718,000 deaths from them in the past 50 years [14]. The western coastal zone is particularly vulnerable to surge flooding due to its low-lying land and very poor defiance against surge waves [15]. A GIS based study showed that a total of 1183 km2 of land has eroded with rate 118.3 km2/year from 1995 -2005 and 1194 km2 from 2005 to 2015 around central part of Bangladesh coastal zone. Major erosions occurred in the areas of Meghna estuary and along the coasts of major islands such as the eastern coast of Bhola, the northern coast of Hatiya and the south-western coast of Sandwip [16]. The future vulnerability in the coastal region of Bangladesh will be significantly higher than present condition [17].Natural disasters such as cyclone, storm surge, floods, and drought will be more frequent and intense in the future. The climate vulnerability will be enhanced in the coastal region of Bangladesh due to geographic settings, dense population, and poverty. central and western part of coastal areas are more vulnerable) because western part mostly covered Sundarbans but it is low lying land areas, other central part is more dynamic part of the coastal zone of Bangladesh.

DELTA PLAN 2100

The government of Bangladesh in cooperation with Netherlands jointly have explored the possibility of drawing up a delta plan for Bangladesh which is integrated and holistic plan, to ensure safe living and sound economic development in Bangladesh. This will provide a complete strategy for development of delta project for next 50 to 100 years. It will be a road map towards of coordinated and prioritized investment in land and water management, continuously bringing in latest knowledge, leading to the desired future in 2100 (Figure 6).DELTA PLAN 2100 HAS THE FOLLOWING

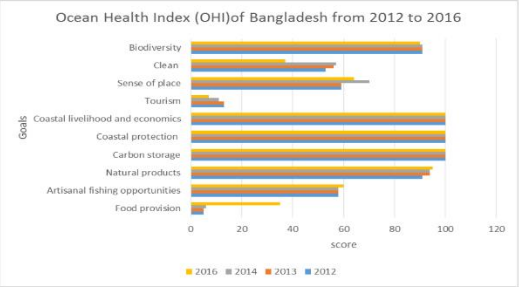


Figure 5: Ocean Health Index (OHI) of Bangladesh from 2012 to 2016.

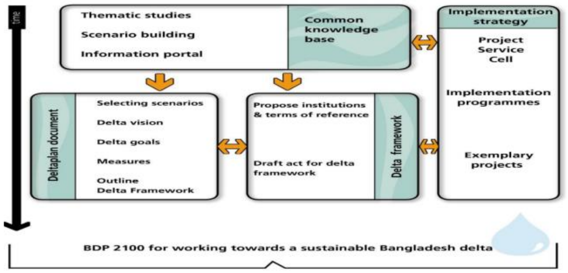


Figure 6: overall process of delta plan [27].

1 Introduction

The Terms of Reference for the NWMPP notes, in NWPo§2.11 that Bangladesh shows considerable regional variability in geomorphological, hydrologic, economic and environmental conditions, which may require tailoring a subset of water resources management goals and objectives to each region. To this end the consultants were required to compile Regional Water Management Programmes.

This Volume therefore presents subsets of the overall NWMP as they agglomerate at the regional level. There is one section for each of the regions, plus one covering the programmes that have national significance. Each section comprises a brief regional overview, a statement of how the NWMP responds to the regional challenges, cost estimated for the regional programmes, or regional portions of shared programmes and the relevant Programme Summary Sheets from the MIS Programmes database.

First however, it is necessary to provide brief mention of the regional delineations adopted for planning purposes. They are in line with the approach adopted for the National Water Plans 1 and 2 prepared in the period 1984-91, and the Flood Action Plan of the early 1990's which divided the country into eight hydrological regions as follows:

- North West
- South Central
- North Central
- South East
- North East
- Rivers and Estuaries
- South West
- Eastern Hills

Figure 1.1 shows the geographical boundaries of the Regions.

It should be noted however, that apart from certain regional issues such as flash flooding in the North East or cyclone risk in the coastal regions, most water sector challenges such as arsenic mitigation; water supply and sanitation are common to most or all of the regions. Solutions are therefore generic rather than specific, and in such cases the regional initiatives are nothing more that regional disaggregations of national or sectoral programmes.

West Region

Overview

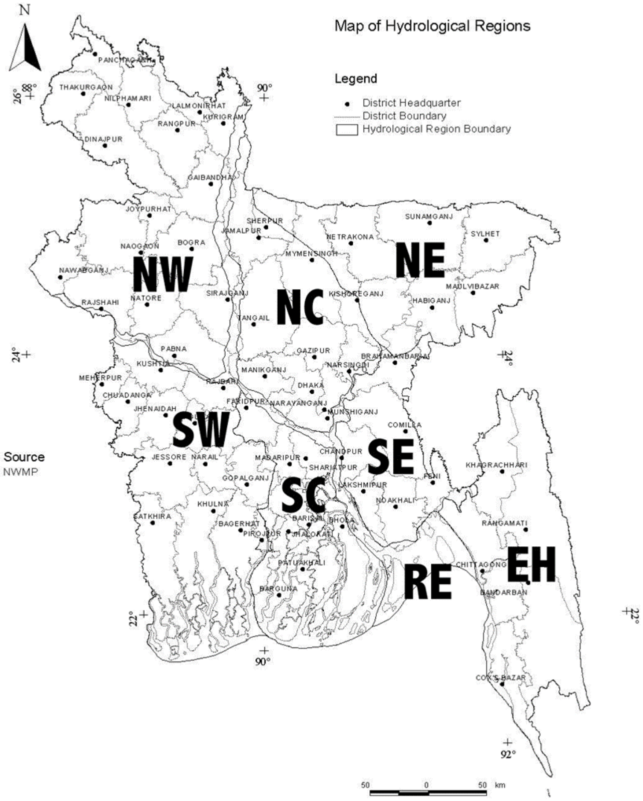
NW Region encompasses the Rajshahi Administrative Division of 16 Districts and is bounded by the Brahmaputra and Ganges rivers. Its total NCA (net cultivable area) is 2.35Mha. Average annual rainfall is about 1,700mm, but its south western part, in the Barind Zone, is one of the driest in Bangladesh, with average rainfall below 1,400mm. The High Barind is the only elevated land. Shallow groundwater is relatively abundant elsewhere.

The region is highly developed agriculturally, with the largest irrigated area of all regions, supplied mainly by STWs. There is less industry than in the country as a whole, although the opening of the Jamuna Multi-purpose Bridge in 1998 and the resultant improvement in transport links with other parts of Bangladesh is expected to accelerate industrialisation. Apart from Rajshahi (current population 0.8M), one of Bangladesh's major cities, Rangpur (0.48M), Bogra (0.42M), Dinajpur (0.37M), Pabna (0.42M) and Sirajganj (0.32M) are the main urban centres.

Severe flooding occurs in the southern part of the region, often for long periods in the monsoon when flood levels in the Ganges and the Brahmaputra are higher than internal river levels. This causes the internal drainage flows to pond up in the lower reaches of the Atrai, Hurashagar and Bangali rivers. Even in relatively dry years, large areas can be flooded for long periods. Some of the country's largest flood control, drainage and irrigation schemes are situated in the Region, notably the Teesta Barrage, the Pabna Irrigation Project, the Brahmaputra Right Embankment (BRE), the Chalan Beel FCD Schemes and the Barind Multipurpose Development Authority's project, which includes a deep tubewell irrigation component.

Apart from meeting the rapidly growing demand for urban water supply, urban and rural sanitation and other water-related services and the problems of environmental degradation and pollution, which are common to most regions, specific water-related issues and problems in NW Region include:

- Erosion along the right bank of the Brahmaptura, which threatens to break through to the Bangali River and is the cause of much hardship to those living in the area. A major project to prevent this happening, the River Bank Protection Project, has recently been completed. A long-term master plan for extending bank protection was formulated under FAP.
- Flooding and drainage problems in areas such as the Lower Atrai and Chalan Beel, and remedial measures for the numerous existing FCD(I) schemes in such areas.
- Drought in the western fringes, especially the High Barind. The existing BMDA DTW irrigation development is one successful attempt at addressing this issue.



Source
NWMP

3 Cen ral Region

3. *Overview*

With a population of 26.3M and an area of about 15,950km^2, NC Region is bounded by the Brahmaputra, Padma and Meghna rivers and by the Old Brahmaputra and Lakhya rivers in the north and north east. Total NCA is 1.06Mha. It is physiographically more diverse than other regions except EH, with the elevated Madhupur Tract, much of which is forested, covering some 2,400km^2 in the centre of the region. Annual average rainfall is 1,400–2,200mm. Like NW Region, shallow groundwater is readily available, except in parts of the Madhupur Tract, and arsenic is not a serious problem except near the major rivers.

With Dhaka (9.0M) and also Gazipur (0.8M), Mymensingh (0.5M), Tangail (0.3M) and other large towns, NC Region is the most urbanised and industrialised in the country. Rapid urban growth is expected to continue in the future. Outside the Madhupur Tract, agriculture is similar to that of the NW Region, with intensive STW irrigation and its accompanying seasonal watertable decline problem. Except in the south, flooding and drainage problems are less and the area of existing FCDI schemes is much smaller.

In NC Region the expansion of urban water-related services and infrastructure will be an even greater challenge than elsewhere, because of the rapidly growing needs of the Dhaka conurbation. Industrial pollution is also particularly serious there. Other water-related issues to be faced in the NWMP include:

- Further raw water supplies for Dhaka City. At present, these come largely from DTWs, with a consequent severe over-exploitation of the local aquifer. The only long-term solution is to bring surface water from one or more of the major rivers.
- Flooding and drainage problems in various parts of the region. These are most serious in the low-lying parts of Manikganj, Dhaka and Munshiganj Districts on the left banks of the Brahmaputra and Padma rivers. However, due to topographic and drainage conditions in this area, it will be difficult to reduce such flooding appreciably.
- Flood proofing needs in the Brahmaputra and Padma river charlands (also covered in the RE Region)
- The possible eventual need for barrages on the Brahmaputra and Meghna rivers.

3.2 *Programme for North Central Region*

Twenty seven programmes will benefit the North Central Region of which four are exclusive to the region. The exclusive programmes are targeted at Dhaka's

East Region

Overview

With a population of 14.9M, 90% of it rural, and an area of about 20,100km^2, the NE Region has distinct differences from NW and NC Regions. Total NCA is 1.41Mha. It is much wetter (average annual rainfall 3,200mm), has relatively little exploitable shallow groundwater except in the north west, due to aquifer problems, but has more abundant dry season surface water resources. Most irrigation is therefore from LLPs rather than STWs. The principal rivers are the Barak (Surma and Kushiyara), Juri, Manu and Khowai.

Apart from tea growing and natural gas production, the region's dominant feature is the 5,600km^2 Haor Basin, containing some 47 major haors and 6,300 beels, of which about 55% are perennial. For fisheries and waterfowl this is the most important wetland area in the country. Due to the deep monsoon flooding (5m or more), partial rather than full FCD is applied here, with submersible embankments which protect the boro crop from flash flooding from the Indian hills in April – May and are then overtopped when the monsoon floods arrive.

There has been less urban and industrial development in NE Region and the largest town, Sylhet, has a population of only some 0.4M. Other important towns are Kishoreganj, Netrokona, Sunamganj, Hobiganj and Maulvibazar, all with under 0.2M inhabitants.

In addition to the provision of better urban services and environmental management and pollution control, major issues to be tackled by the NWMP in NE Region include:

- The arsenic problem, which is found in most of the region
- Environmental management of the wetlands of the Haor Basin, for fisheries and bio-diversity purposes
- Remedial actions for existing FCD schemes. About half the existing FCD area of 0.56Mha has partial rather than full flood protection (ie submersible embankments), which has been found to be preferable to full protection is economic and environmental terms.
- Flood proofing of the 1,000 or so villages in the Haor Basin
- Reducing drainage congestion in the Kalni–Kushiyara and other major rivers
- Local development of hill irrigation

- The arsenic problem
- For environmental and other purposes, restoration of dry season freshwater inflows to the region from the Ganges through the Gorai and possibly other channels
- Maintenance, rehabilitation and, where necessary, improvement of the coastal embankment system and alleviation of its associated drainage congestion
- Remedial actions for the large areas of existing FCDI schemes, especially the GK Irrigation Project.
- Flood proofing in the Ganges river charlands (also covered in the RE Region).

5.2 *Programmes for South West Region*

Twenty nine programmes will benefit the South West Region of which five are exclusive to the region. The exclusive programmes are targeted at Khulna's pressing need for water supply, sanitation, sewerage, flood protection and stormwater drainage and the equally pressing need for salinity control in the Sundarbans.

Shared programmes will address major river abstraction; improved surface water distribution; dredging for navigation; rural and urban arsenic mitigation and flood proofing of key infrastructure.

Institutions and agencies involved in the South West Programmes will include:

- BWDB
- LGI's
- Newly created agencies
- WARPO
- KCC
- LGED
- RHD
- IWTA
- BR

Cost estimates for the South West Regional programmes are provided in Table 5.1.

5 South West Region

5. *Region Overview*

This large region (26,200km^2 and a population of 18.3M) comprises two distinct zones, the inland zone extending from the Ganges and Padma rivers south to around Khulna, and the coastal zone. Total NCA is 1.38Mha. Average annual rainfall is around 1,700mm and, also similarly to the NW, there is comparatively low rainfall area in the west along the Indian border. Arsenic occurs widely throughout the region, but is most concentrated in the groundwater areas adjacent to the main rivers.

Dry season flows down the Gorai river, the main conduit for Ganges river water into the region ceased between 1988 and 1998 due to excessive siltation at the intake from the Ganges, exacerbated by reduced flows in the Ganges following the construction of Farakka Barrage in India in 1975. This has contributed to a significant decline in the quality and extent of the Sundarbans, a mangrove forest of international importance and accorded the status of a RAMSAR site. Although dry season Gorai flows have been partially restored by dredging since early 1999, a permanent solution to this situation remains a pressing need for the region.

The northern and southern parts of the SW region are very different. Almost all the northern inland zone has widespread STW irrigation, and the dry season surface water is generally fresh rather than saline. Cyclones in the northern half are generally not a threat.

Conditions are more difficult in the coastal zone. Most shallow groundwater there is saline and surface water salinity is widespread, with consequently severe constraints on both domestic water supplies and irrigation. Cyclone vulnerability is reduced by the protection afforded by the Sundarbans, but the extensive development of brackish water bagda (Tiger Shrimp) farming has caused severe social and environmental problems. Other major problems include drainage congestion in the coastal polder zone.

In addition to Khulna, a large industrial city and major river port with a population of over 1M, Jessore, Kushtia, Bagerhat, Chuadanga and Jhenaidah, each with a population of over 0.2M, are other important centres. Intensive STW irrigation development has taken place in the inland zone. Here flooding is less of a problem than in most other regions, due particularly to its generally higher elevation, although severe overland flooding from the west occurred in 2000. The main FCDI developments in the region have been the coastal embankment and polder system, built largely in the 1960s and 1970s, and the Ganges–Kobadak (GK) pump irrigation scheme (116,000ha) in the north.

Apart from the issues of urban and rural water-related services and environmental management and pollution control, other issues to be tackled in the NWMP in SW Region include:

6 South Central Region

6. *Regional Overview*

Adjoining the SW Region and bounded by the Padma and Meghna rivers, the SC Region (15,400km^2, 11.1M population) has a similar inland–coastal zone division. Total NCA is 0.93Mha and average annual rainfall is 2,300mm. As the water resource assessment in Main Report Section 3.6 shows, it does not have the same dry season water shortage problem as the SW. On the other hand, it is much more vulnerable to cyclone surges in the coastal zone, partly because it lacks a protective mangrove belt. Like the South West, the region has a serious arsenic problem. In the south of the SC, numerous large tidal channels dissect the land area.

SC Region is less industrialised than the country as a whole and only 12% of its population is urban. Barisal (0.4M), Faridpur (0.16M), Patuakhali (0.15M) and Shariatpur (0.12M) are the main centres. Irrigation is confined largely to the northern, less saline areas, both STWs and LLPs being used. Apart from the coastal embankment system, there are few existing FCD(I) schemes other than the problematic Barisal Irrigation Project.

The north eastern part of the SC is regularly flooded from the Padma river and the river intakes, notably of the Arial Khan, are unstable and frequently changing location. The Padma is morphologically a young river, and attempts to stabilise and/or embank it may well be premature.

In addition to urban and rural services and pollution control, specific issues to be addressed in the NWMP in the SC Region include:

- The arsenic problem
- Maintenance of the existing coastal embankment system
- Siltation and drainage congestion
- Improved cyclone protection
- Flood proofing adjacent to the Padma and in the Padma river charlands (also covered in the RE Region)

6.2 *Programmes for South Central Region*

Twenty five programmes will benefit the South Central Region of which all are shared with other regions. They will address major river abstraction; rural and urban arsenic mitigation; cyclone protection; flood proofing of key infrastructure and coastal protection.

7 South East Region

7. *Regional Overview*

This is one of the smaller regions, with an area of about 10,300 km2 and a population of 13.9M, of which only 11% is urban. Its main towns are Comilla (0.44M) and Brahmanbaria, Chandpur, Feni, Laxmipur and Noakhali, each with a population of 0.2–0.3M. Like SW and SC Regions, it has an inland zone and a coastal zone, with widespread STW irrigation in the former and a serious cyclone risk and drainage congestion and salinity intrusion problems in the latter. It is the region most seriously affected by arsenic contamination of groundwater with between two-thirds and three-quarters of its inhabitants at risk.

Whilst water shortage is generally not serious except in the very south, as is demonstrated by the substantial LLP irrigation development in most of the region. However, there are limitations on overall peak flow requirements and problems with gas in the aquifer, which inhibits tubewell abstraction in the north of the region. Given the high levels of arsenic concentration, it is the region most likely to be at risk to arsenic entering the food chain, and therefore, along with the Southwest, a region which requires very careful and urgent attention.

Bank erosion by the Meghna is serious around Chandpur and other areas, whereas there is major land accretion along the southern shores of the region. In addition to the coastal embankment system and some inland FCD schemes, the region has two major irrigation schemes, Chandpur and Meghna–Dhonagodha.

Apart from urban and rural water-related services, environmental management and pollution control, major issues to be tackled by the NWMP in SE Region include:

- The arsenic problem
- Gaseous aquifers
- Improved cyclone protection
- The existing coastal embankment system and its drainage congestion
- Protection of newly accreted lands against tidal flooding
- Remedial action for existing inland FCDI schemes.

7.2 *Programmes for South East Region*

Twenty six programmes will benefit the South East Region of which all are shared with other regions. They will address major river abstraction; rural and urban arsenic mitigation; cyclone protection; flood proofing of key infrastructure and coastal protection.

8 Rivers and Estuaries

8. *Regional Overview*

This is a new region that was previously not included in either the MPO (Master Plan Organisation) or FAP studies. Its 8,600km^2 cover the floodplains of the three major rivers and the Meghna Estuary. Its 5.8M population lead a precarious existence in these highly active floodplains, where heavy flooding is an annual event. Living standards are low. Erosion along the banks of the major rivers is a major problem, and attempts to train the rivers have often proved difficult and expensive. Low cost solutions have been piloted under FAP, and the results of these need to be taken into account in formulating future strategies.

Bridges have been constructed across the Ganges (Hardinge) and the Brahmaputra (Bangabandhu), and much valuable experience has been gained form these. A second bridge on the Ganges at Paksey is about to be constructed, and one across the Padma is under study.

Cyclone risks are high in the islands of the Meghna Estuary, and land erosion and accretion are widespread there. Apart from the improvement of water supply and sanitation and the wider consideration of long-term sharing arrangements of these transboundary rivers, the main issues in the RE Region to be tackled in the NWMP are:

- An affordable long-term strategy for erosion protection of the main rivers
- An affordable long-term strategy for regional augmentation from the main rivers
- Flood proofing in the Brahmaputra, Ganges and Padma river charlands
- Improved cyclone protection in the Meghna Estuary
- Flood protection on newly accreted lands in the Meghna Estuary, where these have had long enough to build up sufficient height through alluvial deposition.
- The arsenic problem, although this is less severe than in adjoining mainland areas along the rivers.

8.2 *Programmes for the Rivers and Estuaries*

Seventeen programmes will involve the rivers and estuaries. They will address major river abstraction; hydropower development and upgrading; flood proofing and coastal protection.

9 Eastern Hills Region

Regional Overview

The Eastern Hills Region was not covered by the FAP studies. With an area of about 19,950km^2 and a population of 8.9M, it comprises two distinct sub-regions, the Chittagong Coastal Plain and the Chittagong Hill Tracts (CHT). Total NCA is 0.48Mha and average annual rainfall is about 2,400mm.

The CHT has no flooding problems and has some potential for small developments of drip irrigation for high values crops. There are also opportunities for mini-hydropower development. The prospects for large-scale hydropower are limited by environmental and social concerns. Other important issues in the CHT concern the improvement of rural and urban water supplies and sanitation and other water-related urban services in the small number of existing towns.

In the Chittagong Coastal Plain (CCP), the Chittagong conurbation (population 3M) has serious water supply, sanitation, pollution and other water-related problems. Cox's Bazar (0.25M) is the other main urban centre. The whole CPP is protected by an existing coastal embankment system (there is little other existing FCD infrastructure) and there is a thriving bagda shrimp and salt industry. Cyclone risks are high. This was the worst hit region in the 1991 cyclone. Irrigation is mainly by LLPs, STW irrigation being limited by groundwater salinity. There are some arsenic problems in the northern parts of the CCP, but these are less serious than in the neighbouring SE Region. Most of the CCP is water-short, especially with the general lack of useable groundwater. The scope for substantially increasing irrigation water availability is limited by the low dry season flows out of the CHT.

Apart from water-related services and pollution, major issues to be addressed in the NWMP include:

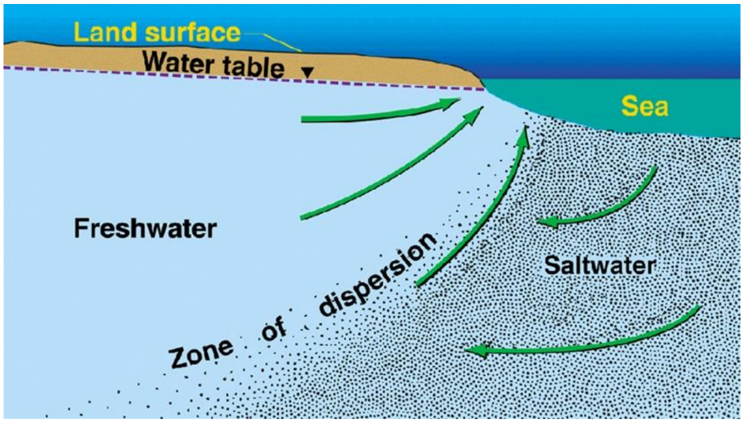
- Small-scale irrigation development in the CHT
- Mini-hydropower development in the CHT
- Improved cyclone protection in the CCP
- Maintenance of the existing coastal embankment system in the CCP

9.2 *Programmes for the Eastern Hills*

Twenty eight programmes will benefit the Eastern Hill Region of which tweenty three are shared with other regions. Exclusive programmes will address Chittagong's pressing need for water supply, sanitation, sewerage, flood protection and stormwater drainage. Shared programmes will address hydropower development and upgrading; urban and rural arsenic mitigation; cyclone protection and coastal protection.

Seawater Intrusion

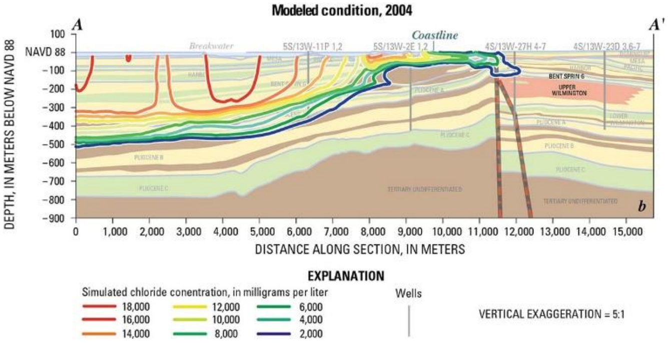
Seawater intrusion associated with groundwater overdraft and lowering of groundwater levels has occurred in many of the coastal aquifers of the United States. The extent of seawater intrusion varies widely among localities and hydrogeological settings. Quantifying the extent and rate of seawater intrusion is key to sustainable management and use of groundwater resources. This involves understanding the aquifer-ocean interconnection, and distinguishing among multiple sources of saline water.



Groundwater flow patterns in an idealized, homogeneous coastal aquifer.

In general, under natural conditions, the seaward movement of freshwater prevents seawater from encroaching coastal aquifers. An interface between freshwater and seawater is maintained with denser seawater underlying freshwater. When groundwater is pumped from a coastal aquifer, lowered water levels can cause seawater to be drawn toward the freshwater zones of the aquifer. The intruding seawater decreases the freshwater storage in the aquifers. Without treatment, this groundwater does not conform to drinking-water or agricultural water-quality standards.

In real-world coastal conditions, the variability of hydrogeologic settings, three-dimensional distribution of saline water, and the history of groundwater withdrawals and freshwater drainage, results in a variety of modes of saltwater intrusion into coastal aquifers with varying complexities (See Los Angeles Basin examples on the *Analysis* tab).These include lateral intrusion from the ocean; upward intrusion from deeper, more saline zones of a groundwater system; and downward intrusion from coastal waters. Saltwater contamination may also occur along open boreholes and within abandoned, improperly constructed, or corroded wells that provide pathways for vertical migration across interconnected aquifers.

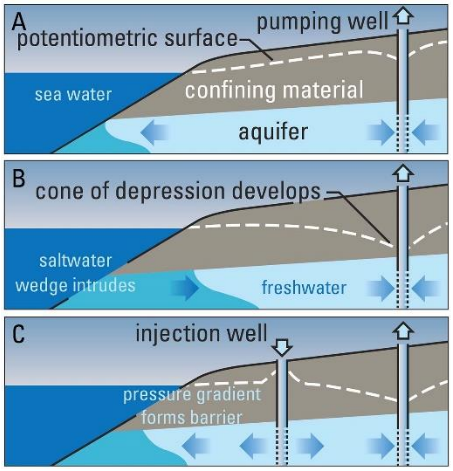


USGS studies show that the geology of the Los Angeles Basin is highly complex, as shown by this modeled figure of Los Angeles seawater intrusion. Dominguez Gap area stratigraphic profile Understanding this geology helps determine where and how fast water moves within the various beds of sediment both onshore and offshore to inform more effective management strategies.

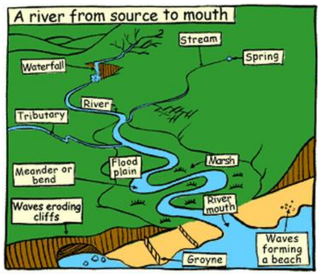
The extent of saltwater intrusion into an aquifer depends on several factors, including the total rate of groundwater that is withdrawn from an aquifer compared to the total freshwater recharge to the aquifer; the distance between the locations of groundwater discharge – such as pumpage from wells and drainage to canals – and the sources of saltwater; the geologic structure of an aquifer or aquifer systems; the distribution of hydraulic properties of an aquifer; and the presence of fine-grained confining units that may limit saltwater from moving vertically toward or within the aquifer.

Potential pathways for seawater intrusion include hydraulic connection to aquifer beds exposed at the sea floor, flow along buried ancient stream channels, and flow through crushed rock in fault zones.

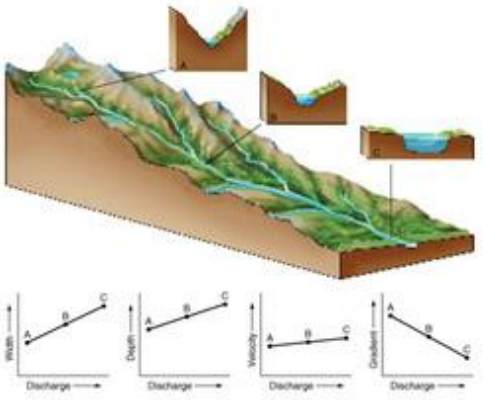
Conceptual figures of Los Angeles seawater intrusion: A. In Los Angeles in the 1800s, the potentiometric surface of groundwater (the levels to which pressure in the aquifer would make water rise in cased wells) was above sea level causing net seaward freshwater discharge from the aquifer. B. Potentiometric surface drops below sea level due to pumping as early as the 1920's causing landward seawater intrusion into the aquifer. C. In the 1950's sets of closely spaced wells were installed to inject high-quality fresh water into aquifers – ideally to stem the flow of seawater



RIVER LANDFORMS



CHANGING RIVER PROFILES

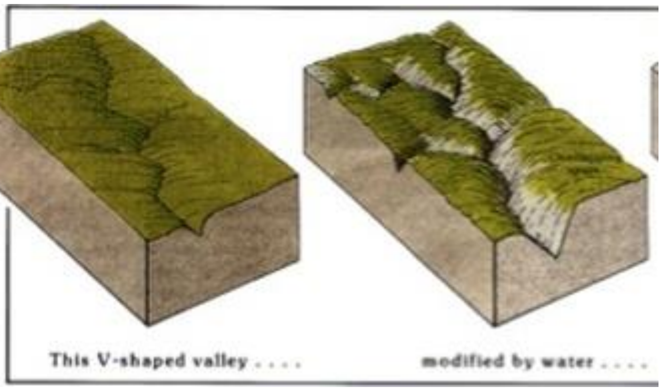


Changing River Profile

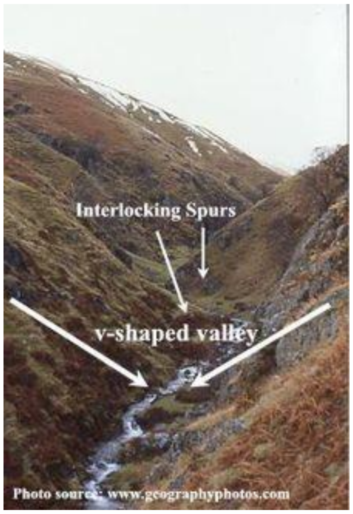
Before looking at specific river landforms it is important to look at how the river channel itself changes downstream. We have already looked at how the river channel in the upper course is shallow and narrow with large bedload that disrupts the efficiency of flow. The bedload is derived mainly from mass movements from the valley sides and eroded rock from the bed and banks of the channel. The valley profile is really just an extension of the channel itself; it follows a symetrical v-shaped form. This narrow valley and river channel is caused by vertical erosion as a result of the high potential energy of the river. As the river stretches downstream both its velocity and discharge increase. Its velocity increases due to more efficient flow and reduced channel roughness. The discharge increases because the catchment area of the drainage basin has increased along with the number of tributaries feeding water into the river. As a result of this increased discharge the river, in its attempt to balance its energy erodes laterally, widening as well as deepening the river channel. At times, the river will exceed the banks and flood across the flatter section of the valley, initially in a youthful phase a floodplain may be eroded out of the valley. Over time a flat extended floodplain devlops either on both sides of the river or dominant on one side. Again in an effort to balance its energy and discharge the river will meander, creating asymetrical river channels; characterised by steep river cliffs on the outside bend of the meander and gentle slip-off slopes on the inside bend of the meander. Unregulated floodplains support permanent and semi-permanent wetlands. Further downstream the floodplain grows in size on both sides of the river as the river channel grows in width and depth. The channel shape becomes once again more symetrical as the channel widens. The meander length and meander belt both increase in size and the erosion of the outside bend slows down.

UPPER COURSE LANDFORMS

V-shaped Valleys and Interlocking Spurs

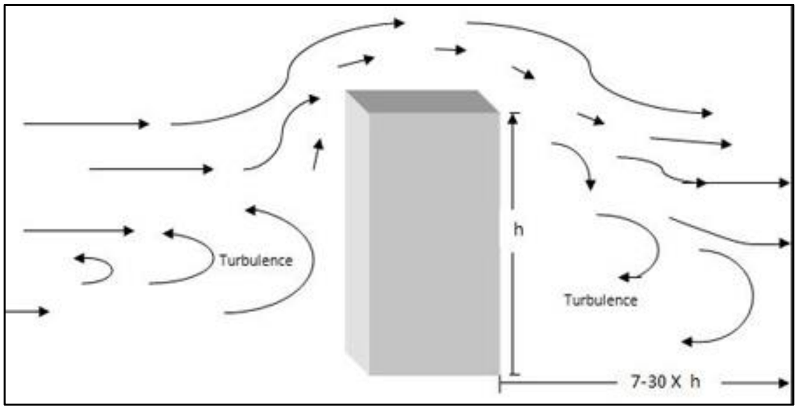


Rivers are constanlty modifying their channel and surrounding landscape. As a result of the potential energy (derived from the gravitional force) as well as its kinetic energy (derived from it movement downslope) the river cuts vertically into channel. This creates initially a deepened channel, as a result of hydraulic action and abrasion; solution may also be present if the river cuts down to the bedrock layer. If this process acted in isolation the channel would take on a very acute, steep v-shape form. However, due to surface run-off, soil creep and other mass movements the valley sides become more gentle. Weathering processes may also aid this breaking down of the valley side. Rivers will always choose to take the most efficient route downslope. If the river flow encounters an obstacle of resistence. e.g. some densely rooted soil, it will change direction and flow around that obstacle. In doing so, it preserves energy and takes the most efficient route. These changes in direction are the birth of hillside spurs. As the river cuts deeper, its valley becomes more pronounced and recognisable. It is normal for a river to make subtle changes in direction repeatedly in its flow downslope; in doing so, interlocking spurs form. These changes in river landscape can be seen in the diagram above and are also also superbly animated below.

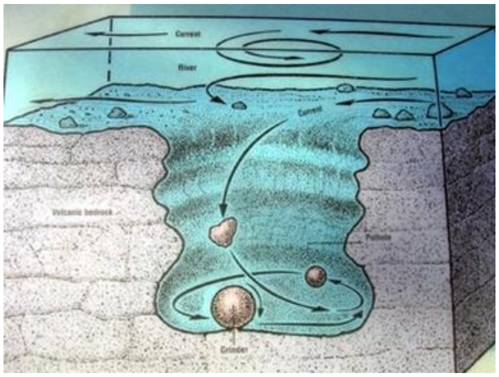


Finally, and very briefly, it is important to understand that the size and scale of v-shaped valleys with their characteristic interlocking spurs reflects the maturity of the landscape. As the landscape matures v-shape valleys become more established. Its channel deepens and at the same time the spurs grow in size. Having said this, v-shaped valleys and interlocking spurs are only a feature of relatively youthful river landscapes. A more mature river valley will have flattened out and developed a floodplain. Weathering and mass movements will have almost fully removed any higher relief. V-shaped valleys and interlocking spurs of varying scale can be sen in the photos below.

POTHOLES



Potholes form mainly in the upper course of the river, in high altitude where the river channel cuts directly into the bedrock. Potholes are the direct consequence of vertical erosion and processes of abrasion. The sequence of the development is quite easy to understand. As we know the river channel in the upper course is characterised by roughness, associated with large bedload. As water flows over still standing bedload on river bed it is forced over the obstacle and to eddie behind the rock downstream. This turbulence forces water down on to the bedrock. Over time small depressions within the bedrock develop. We can see a similar process of turbulent wind movement and eddie development as wind collides with tall building in cities. This is illustrated below.

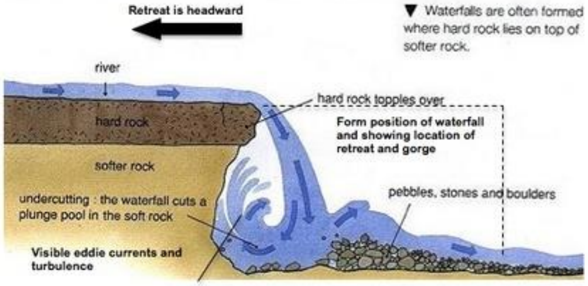


Over time, the turbulent flow deepens the depression in the bedrock to form a small circular basin, just a few centimeters in diameter. This development creates a positive feedback, which further increases the turbulence of the water and the development of eddie currents. It is this turbulence which creates localised variations in the speed of erosion. As we can see in the diagram below, the hollow deepens further to form an established pothole. It is then possible for smaller bedload to become trapped in the pothole. This debris is then used to abrade the sides of the pothole. Over time the pothole will deepen and become more circular; the diameter of the pothole increases in size and often multiple potholes form and merge as shown in the Blyde River. The Bourke Luck Potholes are particularly spectacular as the sand stone bedrock rapidly erodes forming a gorge within the river valley.

RAPIDS

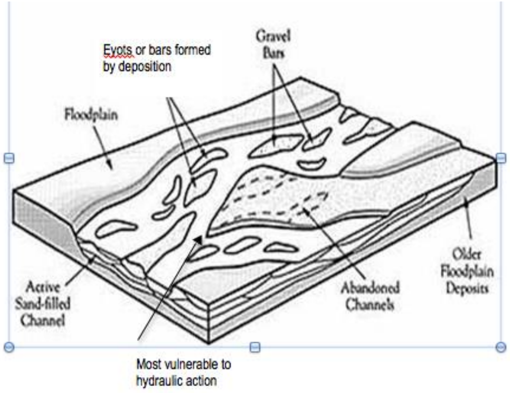
Rapids are most commonly found in the upper course of the river and form as a result of the river cutting down rapidly in a localised section of the river. They may form downstream of a waterfall that has retreated headwardly or they may mark the point of a previous waterfall section. They can be found in other sections of rejuvenating rivers and are located at the knick point of the river. The main characteristics of rapids are distinctly steeper gradients marked by steps in the channel and high turbulence, which is the result of large bedload in the channel or steps. It is common that rapids form over different bands of geology that vary in resistence or where the river is transporting large resistent bedload. The velocity of the river is noticeably faster at rapids but not efficient in its flow. Due to the roughness of the channel, flow is turbulent and known as white water. This white water is thrown up and characterised by eddie currents.

WATERFALLS

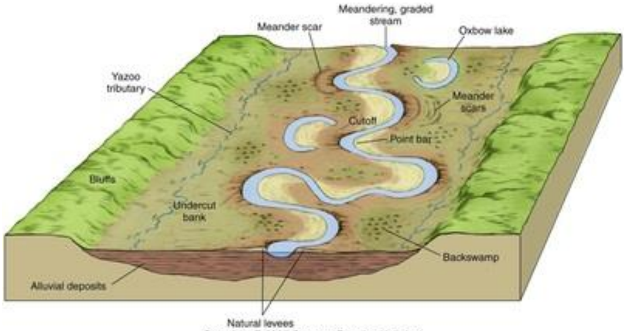

Retreat is headward
▼ Waterfalls are often formed where hard rock lies on top of softer rock.
river
hard rock topples over
hard rock
Form position of waterfall and showing location of retreat and gorge
softer rock
undercutting : the waterfall cuts a plunge pool in the soft rock
pebbles, stones and boulders
Visible eddie currents and turbulence

Waterfalls like rapids form mainly in the upper course as a result of differentiated erosion. If the river channel flows across different bands of geology with varying resistence, then the softer less resistent rock will be eroded faster creating a step in the river. The hydraulic action of the water enlarges this step over time creating the waterfall. Due to the force of the water a deep plunge pool forms at the base of the waterfall. Turbulent flow with eddie currents and splashback undercuts the cap of resistent rock headwardly, untill the undercut is significant enough for the rock above to collapse under its own weight. This leaves angular resistent bedload in the plunge pool, which will combine with hydraulic action to further deepen and undercut through the process of abrasion. Over time the waterfall becomes higher and retreats upstream. As the waterfall retreats a deep gorge with steep U-faced sides forms down the length of the river and marks the length of retreat. Waterfalls are a significant example of both vertical and headward erosion. The process is visualised in the animation below.

BRAIDED CHANNELS


Eyots or bars formed by deposition
Gravel Bars
Floodplain
Older Floodplain Deposits
Active Sand-filled Channel
Abandoned Channels
Most vulnerable to hydraulic action

Braided channels can form nearly anywhere along the course of the river but are most commonly found in the upper course, like with the Yellow River in China or at a river delta where the river breaks up into separate distributaries. Braided channels are common river regimes, which are characterised by significant fluctuations in discharge and resulting capacity to transport bedload. They are common in Alpine rivers with significant snow melt as well as in dry/wet tropical climates that experience extreme rainfall events. Many arid and semi-arid regions have braided river channels.



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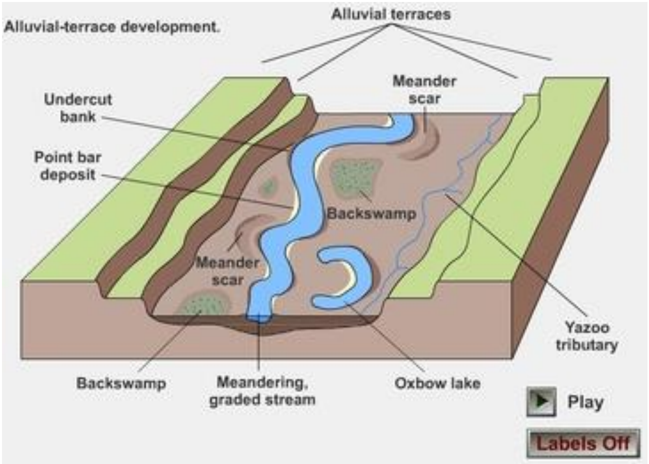
As the diagram above illustrates, braided channels are dominated by multiple channels (braids) and sedimanet bars (eyots). This unique channel characteristic develops due to changes in velocity and discharge. This occurs as part of its typical river regime. During periods of increased discharge, the capacity of the river to transport sediment increases and eyots become eroded. The competence of the river to transport larger bedload also increases. The braids widen and merge. In the timelapse video this process is described as avulsion. Avulsion takes different forms, sometimes expanding into a larger areas of the channel and sometimes sweeping across the channel. In doing so sediment banks shift. During periods of lower discharge, eyots build up due to reduced capacity in the channel. The channel profile is extremely dynamic and complex in its pattern of flow and deposition. The river is constantly converging and diverging in its attempt to find the most efficient route accross the channel. When channels diverge, sedimanet may fill-in between. When channels converge sediment will be eroded. Eyots are in constant change and can extend downstream and upstream depending on the varying pattern of velocity. Separate braids will have different velocities, faster flowing sections are known as chutes. A final but important characteristic of braided channels is the input of sediment. Grainy and loose sediment rather than coagulated sediments are more prone to change in terms of their transportation and erosion. This PowerPoint thanks to SLN summarises braided channel formation.

MIDDLE COURSE LANDFORMS

Floodplain evolution and its associated landforms goes well beyond the development and change of meanders, but many students miss the opportunity in their responses, to develop clear description and explanation of how floodplains develop. Examiners at Post 16 Geography and Geology try to tease student knowledge out by referring to the role floods have in creating specific features. Examiners are really interested in how students are able to assess the relative importance of erosion and deposition. As you can see from the diagram, there is a lot more to discuss than just meanders.

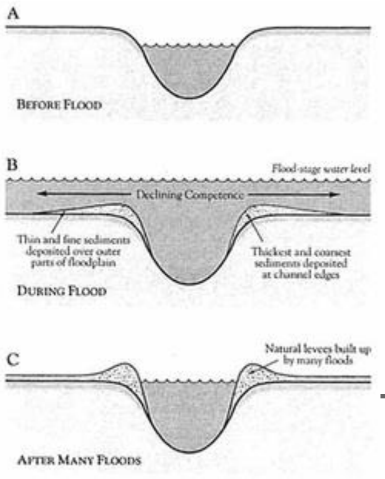
The Development of Floodplains



As we have already learned, rivers increase in discharge as they move downstream. This in turns creates a wider and deeper channel and in the river's efforts to balance its energy the river becomes more sinuous and meanders develop. Intermittently, the rivers discharge will exceed the capacity of the river channel and overflow the river banks. In the early stages of floodplain development, a river cuts out its floodplain as its channel migrates. Channel migration, whereby the river changes direction and location is common in unregulated rivers. Channel roughness is increased due to vegetation growth, fallen trees create obstacles in the channel, even beavers are able to redirect the channel, so that the environment is in constant change. Some rivers like the Amazon have seasonal fllods, which totally submerge the floodplain creating stunning wetland ecosytems with unique flora and fauna. The following video of the River Kissimmee in Florida shows an excellent animation of floodplain inundation.

FLOODPLAIN EVOLUTION

The animation to the left shows how floodplains develop over time. Contrary to the notion that floodplains form through deposition they are in fact cut out by the erosive force of the migrating unregulated river channel. They are contained by the areas of higher relief on their sides, known as bluffs or in the case of rejuvenating rivers, alluvium terraces. The floodplain is well known to be a flat area of land on either side of the river and is made up of deposited alluvium from successive floods. Within the floodplain develop a number of distinct landforms, including levées, meanders, ox-bow lakes and meander scars. Unregulated rivers will also support rich wetlands drained by yazoo tributaries.


A
Before Flood
B
Flood-stage water level
Declining Competence
Thin and fine sediments deposited over outer parts of floodplain
Thickest and coarsest sediments deposited at channel edges
During Flood
C
Natural levees built up by many floods
After Many Floods

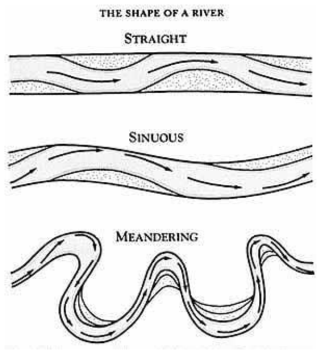
LEVÉES

Natural Levées, Source: Serc Media

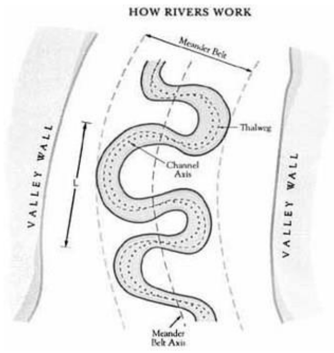
Natural levées form as the river floods its banks and inundates the floodplain. As soon as the river overflows the bank, it comes in contact with greater surface area and friction. This increased friction in turn, reduces the velocity and energy of the river and its ability to transport bedload. As a result, the river has declining competence with distance away from the banks. Consequently, the river deposits its larger load first but continues to transport finer sediments further across the floodplain. The sediment profile therefore falls in size from the bank to the bluff. Due to larger bedload being deposited closer to the bank the bank becomes raised, forming gentle sloping banks towards the floodplain.

Meanders

Meanders are sweeping loops or bends in the middle and lower course of the river caused by rivers developing increased sinuosity downstream. Meanders form through a combination of factors. These factors can be summarised as intrinsic and extrinsic factors. Intrinsic factors relate to the river's attempt to balance its energy, velocity, bedload and discharge. Extrinsic factors relate to the channel gradient and channel roughness.

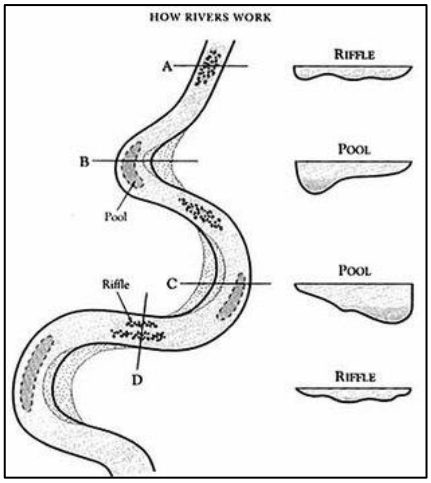


Source: California Rivers and Streams



Source: California Rivers and Streams

There is a lot evidence in rivers to show that as the river flows downstream its sinuosity increases; meanders develop and become more pronounced as discharge and capacity increases. We can observe an increase in both the size of the meander length and meander belt. The gradient of the river will also have an impact on the slow development of sinuosity in the upper course, as flow is moving downslope and eroding vertically rather than laterally. Meander evolution is therefore seen to be an intrinsic response to its own energy and discharge. However, the intrinsic argument doesn't fully explain the initial development of meanders. Something else is at work. As we can see from the shape of the river above, even straight rivers have a small level of sinuosity with the main chute switching from left to right and bars of deposition alternating along the banks. The extrinsic argument suggests that meanders form due to these variations in channel roughness. This often mimicks the valley profile with deposition forming on the flatter side and erosion cutting into the steeper valley. In other cases, a fallen tree or rock develops deposition and once the chute is diverted, a positive feedback develops, which further encourages deposition on one side and erosion on the other. This feedback manifests itself and even accelerates the process over time.

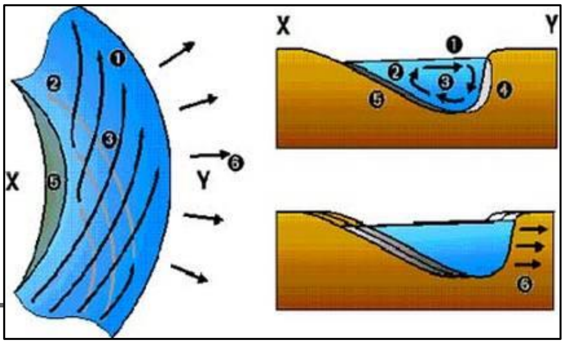


The time-lapse video above shows meander initiation and is useful to see how river flow naturally forms loops as a balance to its energy and discharge. This model shows large variations in discharge so we can observe significant meander migration and braiding. It is useful as well to see how meander migration helps cut out a wider floodplain and form alluvium terraces.

MEANDER EVOLUTION AND OX-BOW FORMATION

A positive feedback of increased velocity and erosion follows the line of fastest flow (thalweg) to the outside of the bend cutting out the river cliff and deepening the pool. Slower flow and deposition develops a point bar or slip-off slope on the inside of the bend. This can be seen in the asymetrical cross-profile at B. Overtime as the meander becomes more established the pool deepens as shown at C. Riffle cross-profiles develop between the loops on the straight sections. These are shallow sections, characterised by the deposition of bedload scoured from the river cliff of the previous meander loop. The pattern of riffle and pool distribution corresponds directly to the meander length.

It is important at this point to examine in more detail, the proceses at work at the cross-profile of the meander.

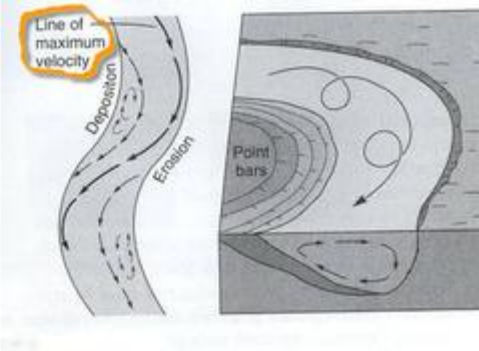


HELICAL FLOW

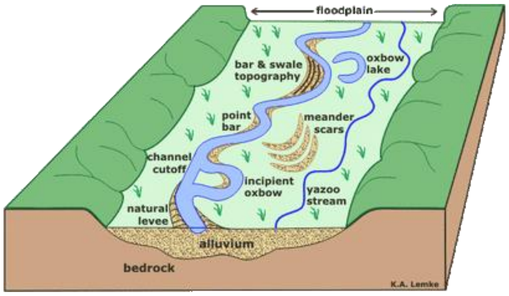
Text and diagram adapted from www.oxbowriver

The helical flow of water plays an important role in the formation of meanders, especially in developing river cliffs and slip-off slopes. Higher velocity chutes within a stream tend to be driven to the outside of a meander seen at point 1. On the outside of the meander, the surface of the water has a tendency to be slightly higher because it has gained momentum and acceleration, in the same way as centrifugal force works. Here, the flow is forced down the outer bank which results in the scouring of the bank and bed. It returns to the surface toward the inside of the meander where flow is less turbulent, seen at point 2. This flow across the channel is known as the secondary cell. This can be seen in the diagram below.

The helical flow continues to erode the outside of the bend and deepens the pool. At the same time it redistributes scoured material and deposits it on the slip-off slope and riffle section. This continuous process cause meanders to migrate and contract at their neck. Overtime the meander neck becomes narrower untill the river cuts directly through, forming a channel cut-off and incipient ox-bow as seen below. In time, the incipient ox-bow will be cut off entirely through deposition to form an ox-bow lake. Ox-bow lakes have a



Helical flow in a meander.

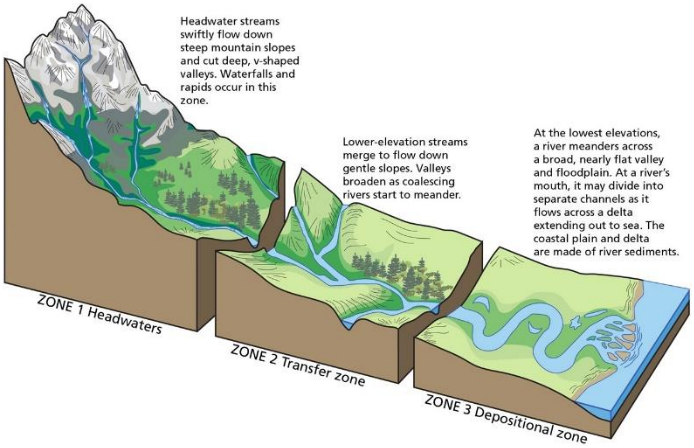


Introduction

Fluvial systems are dominated by rivers and streams. Stream erosion may be the most important geomporphic agent. Fluvial processes sculpt the landscape, eroding landforms, transporting sediment, and depositing it to create new landforms. Human civilization and ecosystems alike are dependent on fluvial systems. Rivers provide water for hydroelectric power and shipping, as well as supporting stream-side wetlands (riparian areas) that are critical for clean water and provide rich habitat.

The drainage basin or watershed is a fundamental landscape unit in fluvial geomorphology. A dranage basin contains a primary, or trunk, river and its tributaries. Watersheds are separated from their neighbors by a divide; a highpoint where water flows in different directions on either side.

- **Upper Basin** Headwaters
- **Mid-basin** Low gradiant valleys and flood plains
- **Lower Basin** Depositional Zone

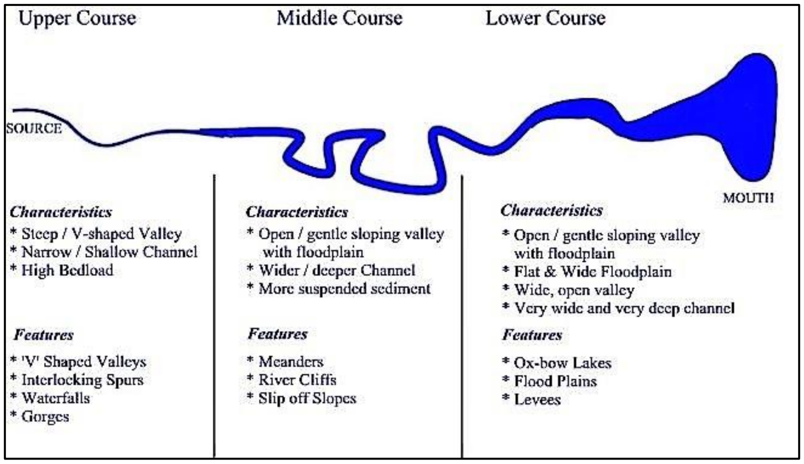

Headwater streams swiftly flow down steep mountain slopes and cut deep, v-shaped valleys. Waterfalls and rapids occur in this zone.
Lower-elevation streams merge to flow down gentle slopes. Valleys broaden as coalescing rivers start to meander.
At the lowest elevations, a river meanders across a broad, nearly flat valley and floodplain. At a river's mouth, it may divide into separate channels as it flows across a delta extending out to sea. The coastal plain and delta are made of river sediments.
ZONE 1 Headwaters
ZONE 2 Transfer zone
ZONE 3 Depositional zone

Floodplain Landforms

In addition to the streams themselves, the depositional habits of fluvial systems produce striking landforms. Fluvial deposits are sediments deposited by the flowing water of a stream.

A floodplain is the relatively flat surface adjacent to the river or stream. During floods, when the stream overflows its banks, water flows over the floodplain and deposits sediment. Through fluvial processes, streams construct floodplains that accommodate their maximum flood capacity. Geomorphic features of the floodplain include:

- Natural Levees—River may be immediately flanked by a buildup of sediment that forms natural levees. These provide some defense against flooding, but are occaisionally breached in areas producing flood-plain splays—coarse fan-shaped deposit of sediment created during high flow events.
- Oxbows and oxbow lakes—See below, features of a Meandering Stream Channel.
- Point Bars—See below, features of a Meandering Stream Channel.
- Terraces



Channel Morphology

The shape that a stream takes, or its channel morphology, is a function of the sediment carried and deposited by the stream. This divides medium to low gradiant streams into two general categories, **meandering** and **braided**.

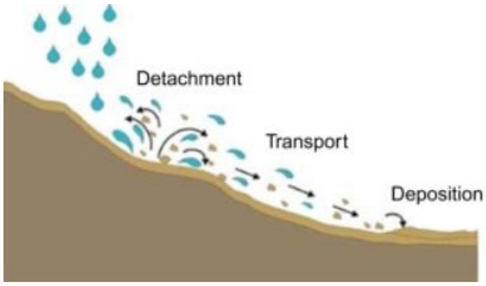
Fluvial Features—Meandering Stream

Meandering channels form in low gradient zones where a stream is moving fine sediments by eroding outer bends and depositing on inside bends.

Fluvial Features—Braided Stream

Braided streams and rivers have multi-threaded channels that branch and merge to create the characteristic braided pattern. Braided channels are highly dynamic with mid-channel bars which are formed, consumed, and re-formed continuously.

What is Rill Erosion?



The signs of rill erosion appear mainly on hills, and appears as a 0.3 to 3.9-inch deep set of channels that run parallel but may converge at some points. Runoff water forms these channels as it concentrates and then flows down a slope.

There is a distinct flow pattern to rill erosion which means that the water runs through these predictable, if disconnected, parallel channels.

Over time, the soil profile wears down and becomes increasingly thinner with each rainfall. Once the slope tapers off and flattens at the base, soil particles sit there, deposited into a terrace or are carried further into principal waterways.

Once the channels formed by rill erosion reach four inches, they become gullies. The width, depth, and flow strength of gullies are much more significant.

At this point in their development, rill eroded channels displace soil and nutrients, and the sediment carried along can cause some clogging. However, these channels are not yet wide enough to be a significant issue.

WHAT CAUSES RILL EROSION?

Rill erosion is most noticeable on a hillside or a slope. Once it accumulates on the surface of soil sitting on a slope, water runoff can't help but flow downhill.

In a way, rill erosion is the consequence of poor water infiltration into the soil. This, in turn, is caused by a poorly structured soil makeup that can't absorb all the water delivered. It's a trickle-down effect.

Factors that trigger rill erosion include:

- **Poorly structured soils** — are prone to break up during through the impact of rainfall
- **Nature of the soil itself** — Clay soils, for example, vary in how well they can withstand aggregate raindrop impact
- **Rainfall intensity** — The higher and more frequent rainfall, the greater the risk for soil to seal, preventing water from penetrating below the surface
- **Slope length** — On long slopes, water has more time to collect momentum and soil particles
- **Slope angle** — The angle affects the speed of the runoff, which then increases the power of the water to break of soil particles and carry them through the rills

The most compelling reason to address and curb rill erosion is that it's the first stage of a more severe issue called gully erosion. Once channels reach a depth of four inches, thanks to water flows carving a track in the same place, there's no going back — you've officially entered gully erosion.

What is Gully Erosion?

In theory, if there were no underlying rock to stop erosion process, gullies could be as wide and deep as the water power flowing through them could cut and shape them to be. Gully erosion is a highly visible form of soil erosion which can indicate an imbalance in regular watercourse flow. Larger (and faster) than normal water flows cause steep-sided watercourses which then widen further during periods of heavy rainfall.

(Image Source)

As the water flows with full force through these gullies, the cycle of degradation continues. Soil particles are picked up and deposited elsewhere, causing blockage and siltation in waterways, dams, and reservoirs.

Suspended sediments also include all-important nutrients and pesticides, which then reduce water quality. Once these fine deposits of soil clog groundwater aquifers, they can pollute main watercourses and negatively affect the breathing patterns of aquatic life.

Besides these issues, the harmful effects of gully erosion include restricted land use, reduced soil productivity, damage to roads, fences, and buildings, and even extremely high populations of pests such as mosquitoes around gully-prone areas.

WHAT CAUSES GULLY EROSION?

A whole range of factors trigger gully erosion, including:

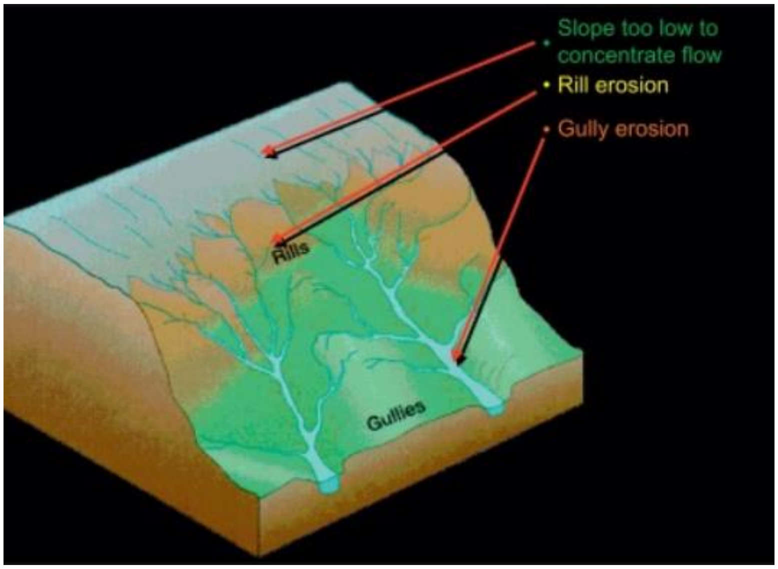
- Cultivating or grazing on soils that previously identified as vulnerable to gully erosion
- Runoff from events like tree clearing in a catchment or construction of new residential areas
- The building of structures like waterways, contour banks, tracks, or roads
- Poorly designed construction or maintenance waterways in cropping areas
- Poor vegetative cover because of issues like brush fires, salinity, and overgrazing
- Diversion of an established drainage line to soils that already have a high risk of erosion, for example, up a steep creek bank or highly erodible soils

Once a gully becomes wide and deep enough, they're a hard problem to fix and heal. If you can catch and repair the land during the early stages of a newly formed gully, you may be able to stop it from spiraling to the point of no return.

Gully erosion affects more than just the surrounding land and the ecosystem. The unsightly channels that the eroding process creates can reduce amenity and property values, as well as destroy any agricultural capacity the land has for farmers.

How to Control Rill and Gully Erosion

Even though rill erosion is not as extensive a problem as gully erosion, there are situations in which rills can transform into gullies. As you can see in the erosion diagram below, rills that begin at the top of a slope can quickly disintegrate and branch off into their wider gully counterparts.



(Image Source)

To fix the issue at either the rill stage or the gully stage calls for a two-pronged approach: first, to reduce and re-divert the flow of water into stable drainage lines, and secondly, to then stabilize the gully itself.

You don't have to look farther than natural solutions to execute on both of these strategies:

- Using trees and deep-rooted perennial pastures to soak up excess water and reduce runoff (identifying which areas can be used for planting and soil improvement)
- Maintaining farm tracks and culverts for drainage — this ensures that water flows evenly dissipate and don't concentrate in any one specific area
- Creating diversion banks to distribute water over well-vegetated areas
- Using "contour cultivation," the farming practice of planting across a slope following its elevation contour lines, to slow down and even break up the pace of the water flow. This helps it spread over a wider area and reduces the chances for gully formation over time.

Until the restoration of gully-eroded areas is complete, there can't be any livestock feeding or agricultural farming projects nearby. Erosion control methods and revegetation are effective processes but they take time — especially if the damaged area covers several properties and needs some level of cooperation and collaboration from individuals.

Stream Channel Pattern

Stream flows are generally irregular, confined to channels that give it a three-dimensional nature and are visible through variations in channel patterns. The smooth and regular-stream flow will result in straight and direct steam channels, but it is obvious that in nature very few streams exhibit straight and uniform channels over a long distance. Most steam channels tend to wind their way across the landscape, sometimes showing great sinuosity.Stream channel patterns can be Straight, Sinuous, Meandering and Braided. Any large river system, such as Ganga or Brahmaputra, is made up of all four types of channel patterns.

Straight Channel: These are short and uncommon and reflect a strong structural control due to underlying rock formation. A straight channel would not mean that a river is running in a straight line. The deepest part of the channel, known as thalweg, hardly ever follows an absolutely straight line and may move right and left across the channel.

Sinuous Channel: These are winding channels most commonly found in various topographical structures. The channel exhibits sinuous characteristics even when the stream flows down a steep slope with a high gradient. On a flat topography with a low gradient, steam channels flow with greater sinuosity.

Meandering Channels: These are most common and are depicted by a serpentine course contorting and curving, showing twisting behaviour. The word meander means to proceed sinuously and aimlessly. Flat topography with low gradients is characteristic of meandering channels where in most streams have fine sediment loads.

The meandering channels have cohesive alluvial banks, and the sinuosity of the river is expressed as the ratio of the river channel length over the valley length. It can depict varying ratios, including one. The wavelengths are tightly clustered around a dozen times the width of a typically meandering river (Anderson & Anderson, 2010).

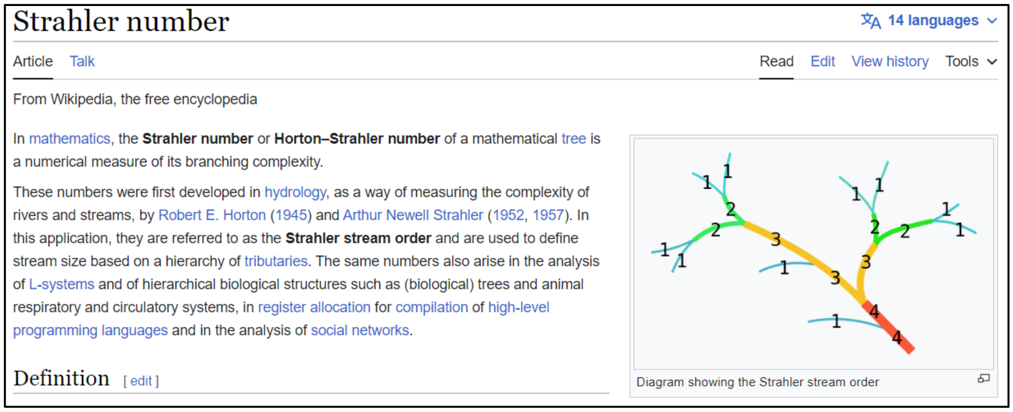
The inside bend of the meander may have a sandy deposit termed a point bar – forming part of the active drainage system. The thalweg will be located on the outside bend against the river's far bank. Scroll bars and oxbow lakes are the geomorphic expressions of the meandering system.

These are commonly observed in the Mississippi Valley of North America. In India, the fluvial flood plain of River Burhi Gandak in Bihar shows several scroll bars and Oxbow lakes.

Braided Channels: These comprise multiple interwoven and interconnected channels that may be separated by low bars or islands of sand, gravel and other loose debris (McKnight, 1998). The pattern of the braided channels is explained through the process in which the banks lack cohesion, transport is by bedload only, and the flow of water in the stream fluctuates frequently.

These patterns are common in glaciated landscapes as glacial outwash plain channels where the coarse-grained bed load is supplied by a glacier to the meltwater. In arid landscapes with dry seasons and periods of low water discharge predominates the streams show the characteristic braided channel.

Since there is a deficiency of fine material and vegetation, there is a lack of cohesion in the river banks. The flow in the braided channel at any given point of time occupies two or more channel segments simultaneously. The flow threads are separated by mid-channel bars. Sometimes the entire valley cross-section may have many tens of threads.


Strahler number

From Wikipedia, the free encyclopedia

In mathematics, the **Strahler number** or **Horton–Strahler number** of a mathematical tree is a numerical measure of its branching complexity.

These numbers were first developed in hydrology, as a way of measuring the complexity of rivers and streams, by Robert E. Horton (1945) and Arthur Newell Strahler (1952, 1957). In this application, they are referred to as the **Strahler stream order** and are used to define stream size based on a hierarchy of tributaries. The same numbers also arise in the analysis of L-systems and of hierarchical biological structures such as (biological) trees and animal respiratory and circulatory systems, in register allocation for compilation of high-level programming languages and in the analysis of social networks.

Definition [edit]

Diagram showing the Strahler stream order

This means that at any given point in time, active channels may cover less than one-tenth of the width of the entire channel system. But in a year, most or all of the surface sediments may be reworked by the lateral flow in the stream channel.

The flow depths may range to a few metres only. As the flow depth increases, the shear stress exerted on the bank becomes sufficient to entrain bank material, and the channel widens locally (Anderson & Anderson, 2010).

Chitina River, Alaska, shows extensive braided stream channels and is formed from major glaciers of the Wrangell Mountains.